

The Microwave Anisotropy Probe Guidance, Navigation, and Control Hardware Suite

*David K. Ward, Systems Engineering Branch
Gary T. Davis, Propulsion Branch*

*NASA Goddard Space Flight Center
Greenbelt, MD 20771 USA*

The Microwave Anisotropy Probe (MAP) was launched June 30, 2001 to create an all-sky map of the Cosmic Microwave Background. The mission's hardware suite included two Lockheed Martin AST-201 star trackers, two Kearfott Two-Axis Rate Assemblies (TARAs) mounted to provide X, Y and redundant Z-axis rates, two Adcole Digital Sun Sensor (DSS) heads sharing one set of electronics, twelve Adcole Coarse Sun Sensor (CSS) eyes, three Ithaco E-sized Reaction Wheel Assemblies (RWAs), and a Propulsion Subsystem that employed eight PRIMEX Rocket Engine Modules (REMs). This hardware has allowed MAP to meet its various Orbit and Attitude Control Requirements, including performing a complex zero-momentum scan, meeting its attitude determination requirements, and maintaining a trajectory that places MAP in a lissajous orbit around the second Sun-Earth Lagrange point (L2) via phasing loops and a lunar gravity assist. Details of MAP's attitude determination, attitude control, and trajectory design are presented separately. This paper will focus on the performance of the hardware components mentioned above, as well as the significant lessons learned through the use of these components. An emphasis will be placed on spacecraft design modifications that were needed to accommodate existing hardware designs into the MAP Observatory design.

MAP's requirement of 1.3 arcminutes, RSS of three axes, necessitated the use of a star tracker for attitude determination. For this task, the project selected the Lockheed Martin AST-201, a quaternion-output tracker that was modified to autonomously track stars at rates up to $3^\circ/\text{second}$ in order to work during MAP's all-sky scan. As is discussed separately, both of MAP's trackers have easily exceeded MAP's requirements, providing quaternions that are accurate to better than 2 arcseconds with respect to their boresights (<30 arcseconds about the boresight) during either Inertially-fixed or spinning operations.

Some credit for the excellent stray light performance of the AST-201's should be given to MAP's sunshield design, which keeps the entire spacecraft shaded during Observing Mode operations in order to keep the Instrument passively cooled. Originally, it was thought that MAP's solar panels and multilayered thermal blanketing would be sufficient to keep stray light away from the star tracker, so a shorter (5") stray light baffle was selected for both trackers to save mass. During launch site preparations, it was discovered that small perforations added to the thermal blanketing to improve surface conductivity actually allowed the blankets to transmit light onto the back surface of the solar arrays, into each star tracker's stray light field of view. A modification nicknamed "the batwing" was made to the blankets in the trackers' stray light fields of view. An additional layer of conductive black kapton covered the transmission paths while not sacrificing surface conductivity requirements, while a curved surface nicknamed "the

jellyroll" added a layer of diffraction protection at the edges of the arrays. This design has worked wonderfully on-orbit, with very few instances of stray light contamination through the mission and none once in normal Observing Mode past the Moon.

The perpendicular spin of MAP's Observing Mode relative to both of the star tracker boresights also allowed the ACS team to find and fix an error in the attitude determination algorithm. Since the AST-201 design does not include an interface to determine the tracker's inertial location, the velocity aberration correction algorithm is implemented in MAP's spacecraft computer. During In-Orbit Checkout, the difference between the "corrected" quaternions for each tracker was seen to vary in a sinusoidal pattern with amplitude of approximately 20 arcseconds. A flight software table load corrected the aberration correction algorithm, and the sine wave disappeared. This experience suggests an on-orbit test that can be performed to verify the velocity correction algorithm, eliminating a possible source of error for future missions.

As mentioned above, MAP uses two Kearfott TARAs for rate determination and attitude propagation. Both TARAs have performed on-orbit as expected, easily meeting the requirements of the MAP mission, but their unique interface required specific improvements to the MAP software to ensure their performance was met. Instead of performing scale factor temperature compensation within each TARA, the compensation equations are provided to the spacecraft to compute relative to an analog measurement of gyro temperature. This design choice eliminates an additional round of calibration and testing, and makes sense given the TARAs position as a lower-cost alternative to higher-performance gyros. The analog temperature interface comes out of each TARA by separate pins that are driven by the same analog driver. On MAP, those pins are connected to redundant Attitude Control Electronics (ACEs), both synchronized to the main spacecraft processor. Since both ACEs run the same software, it is possible for the TARA analog interfaces (the gyro motor current uses a similar interface) to be read by both ACEs at once, with the unfortunate consequence that one will corrupt the analog-to-digital conversion of the other. This would have the effect of disrupting the scale factor calculation for one ACS cycle, a possibly significant performance impact given the 3°/second scan rate. Two separate modifications were made to the ACS software to fix this problem. The ACE software was modified to introduce a delay in the A/D conversion on one of the ACE's, so that the process would not be synchronized. This greatly reduced the chances of a A/D corruption, but did not eliminate the possibility since each TARA analog shared a multiplexor address with other analogs that would be converted at nearly the same time. To address this problem and the separate problem of a Single Event Upset in the A/D conversion circuit, software was added that ignored analog signals that produced too large of a step change in one cycle. This second change also provided some protection to sudden failures of the analog outputs from not only the TARAs, but the Reaction Wheel tachometers as well.

Both the Coarse and Digital Sun Sensors used for MAP are standard Adcole designs that have been used on previous NASA GSFC missions. As such, their use produced few design surprises, but an examination of uncalibrated on-orbit data shows the importance of proper calibration for use in fault detection or rate derivation. MAP's twelve Coarse

Sun Sensor eyes (six per ACE) showed exceptional performance through the early phase of the mission, during Sun Acquisition and Inertial Hold on the sunline. The agreement was better than 2° , and generally can be attributed to the lack of albedo experienced by MAP through its mission trajectory. On the other hand, once the spacecraft was slewed out to the 22.5° sun offset, the CSS algorithm calculated a 30° sun angle. Had it been genuine, this sun angle would have been enough to thermally shock the Instrument, thus it resulted in an FDC failure that normally would cause a switch to Sun Acquisition Mode. Quick work by the Flight Operations Team avoided this FDC action, but the apparent discrepancy between the sunline data and other data needed to be studied. The results are not surprising, considering the MAP CSS algorithm was designed with the assumption that each CSS provided an output relative to the cosine of the angle between the boresight. While that is an appropriate approximation, the field of view of each sensor is actually limited to $\pm 80-85^\circ$, and the orientation of the eyes introduced errors between the expected and actual output as the spacecraft sun angle increased. Interestingly, the errors began to decrease once the spacecraft sun angle passed 30° , so concerns about orbit adjust maneuvers performed at a 45° spacecraft sun angle were not realized.

The calibration of the Digital Sun Sensor became important in the context of its use as a replacement for a failed TARA rate axis. Adcole provides nine calibrated coefficients for each axis of its DSS, but the default coefficients were mistakenly loaded at launch and through IOC. Rate performance during this period shows the risk with using improperly calibrated sensors. In particular, the DSS X-axis rates show up to $0.1^\circ/\text{second}$ rate errors as compared with TARA rates. NASA GSFC's Flight Dynamics Facility has developed a twelve-coefficient DSS calibration that enhances Adcole's nine-coefficient calibration with three cross-axis coefficients. The result of this calibration is seen in DSS rate and attitude performance, where rate errors have been reduced to $0.02^\circ/\text{second}$, commensurate with attitude accuracy to 1 arcminute. The performance of the DSS Y axis is even better, with rate errors less than $0.005^\circ/\text{second}$, and attitude errors on the order of 15 arcseconds.

MAP uses two separate sets of actuators to perform attitude control in the different phases of its mission: REMs for control during orbit adjust and momentum unloading maneuvers (known on MAP as Delta V and Delta H, respectively), and RWAs for control during each of the other modes (Sun Acquisition, Inertial, Observing, and Safehold.) Performance of both sets of actuators have been within specification, with each REM producing a thrust within 5% of the "as designed" thrust and each reaction wheel producing up to 0.215 Nm of torque with less than 0.025 Nm of torque error. Nonetheless, each actuator has produced unexpected lessons learned during the IOC phase.

A lesson of particular importance to the performance of Observing Mode was the need to calibrate the RWA tachometer signals from each wheel. As mentioned earlier, each wheel produces an analog signal to indicate the wheel's speed. In Observing Mode, these

signals are used in a feed-forward loop to counteract gyroscopic torques produced by the spacecraft's spin crossed with RWA momentum. Unfortunately, these signals were not well calibrated at launch, resulting in Observing Mode pointing errors. The most obvious symptom of this error could be found in the spin-frequency variation in the calculated system momentum (which should be nearly constant), as well as the step change in the same measurement as the spacecraft spun-up from Inertial Mode into Observing or vice-versa. A comparison between flight data and a High-Fidelity simulation determined a 2.5% error in the RWA 1 tach scale factor, 4.2% error on RWA 2, and 4.5% on RWA 3. Observing Mode attitude control and system momentum data taken after the RWA calibrations were updated show a significant improvement in performance.

The thrusters also provided surprises during IOC, though their performance through each of the Delta V maneuvers would be considered exemplary. The first unexpected lesson occurred during the first use of the thrusters. A conservative operations plan called for short pulse tests for each thruster prior to their use in either Delta V or Delta H Mode. This test used ground commands to pulse each thruster separately for 0.4 seconds and to determine the resultant force and torque by the change in system momentum. The test was to be repeated twice per thruster, as there was some concern about bubbles in the Hydrazine fuel between the valve seats in each thruster. The first set of thruster firings resulted in thruster scale factors that were only 65-75% of their "as designed" values, a result that was not wholly unexpected given the possibility of bubbles discussed beforehand. When the second test results (as well as results from tests performed on the other ACE a day later) also resulted in the same scale factors, the bubble theory was discarded. Inspection of thruster temperatures during each firing provide the actual reason for the lower scale factor: the thrusters required on the order of 1-2 seconds to reach steady-state temperature (and thrust), so a brief pulse is adequate to determine the functionality of a thruster, but not to calibrate its thrust scale factor on-orbit.

MAP's initial Delta V calibration brought the final lesson to be discussed. The MAP propulsion subsystem was designed without pressure regulators, as an unregulated "blowdown" system. An anticipated blowdown is calculated for each burn, as this pressure change is an important factor in the thrust to expect for a burn. During the first calibration burn, the pressure dropped lower than predicted, then rose to the predicted level after the burn completed. This unexpected pressure behavior is caused by the exceptional thermal isolation of the fuel tank. The propulsion team's model assumes isothermal expansion of the nitrogen gas used as a pressurant in the tank, but the tank's insulation makes the system behave more like an adiabatic expansion. Thus, the pressurant was actually cooled during the calibration burn due to the sudden expansion of ullage volume, resulting in the larger than anticipated drop in pressure. The change was most pronounced during the first burn, since the percentage change in pressurant volume was the greatest during that burn. This effect did not significantly change Delta V maneuver planning or execution; after the first burn, the effect was significantly reduced by the smaller change in percentage of pressurant volume and the longer burn time, which allowed the external heat to warm the pressurant to steady state.